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NEUTRON STARS AS COSMIC NEUTRON MATTER LABORATORIES

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ABSTRACT

Recent developments which have radically changed our understanding of the dynamics of neutron star superfluids and the free precession of neutron stars are summarized, and the extent to which neutron stars are cosmic neutron matter laboratories is discussed.

1. Introduction

Remarkable progress has been made in the past few years in both theory and observation relevant to understanding the structure of neutron stars and the behavior of the neutron superfluids that make up the greater part of these stars. Indeed, it may be argued that it is now possible to use neutron stars as cosmic neutron matter laboratories, in that by combining theory and observation one can obtain detailed information (unobtainable in any other way) on the nature of the neutron superfluids in the stellar interior, as well as on the equation of state of neutron matter at densities equal to or somewhat greater than that found in laboratory nuclei. Space does not permit me to describe this progress in any detail in these proceedings; I shall therefore simply summarize briefly some major developments and refer the reader interested in more detail to recent

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reviews,[1,2] and accompanying articles in this volume.[3,4]

2. Neutron Superfluids

Two distinct neutron superfluids are expected in neutron stars:

- in the inner part of the crust, at densities, 4×10^{11} gm $cm^{-3} \lesssim \rho \lesssim \rho_o$, a ^1S_o paired superfluid coexists with a lattice of crustal nuclei
- in the liquid core ($\rho \gtrsim \rho_o$), a $^3P_2$ paired superfluid coexists with a comparatively small fraction (~5%) of superconducting protons and normal relativistic electrons.

Our current understanding of these superfluids is that:[2,3]

- the core superfluid rotates rigidly with the crust
- because of the pinning of vortices in the crustal superfluid to crustal nuclei, the crustal superfluid, which contributes $\lesssim$ 10% of the stellar inertial moment, can be out of equilibrium with the crust for timescales of weeks to years and is responsible both for pulsar glitches and post-glitch relaxation
- vortex creep theory, which describes the motion of pinned vortex lines in the crustal superfluid, provides an excellent fit to the Vela pulsar timing observations of Downs,[5] which span the decade 1969-79 and include four giant glitches, as well as to the Crab timing observations of Lohsen,[6] which span the decade 1969-79, and include two large glitches, and the observation by Downs[7] of a glitch and its consequences in PSR 0525+21.[8]
- the observed post-glitch relaxation times in the Vela and Crab pulsars, and PSR 0525+21 provide a means of estimating the interior temperature of these pulsars
- interior temperatures of the Crab and Vela pulsars obtained in this way, while consistent with observations, are not consistent with a standard cooling scenario[4]
- the dominant source of heat in pulsars old enough to have

radiated away their original heat content is vortex creep

- strong pinning of vortices to crustal nuclei is ruled out by an upper limit on the rate of dissipation of energy by vortex creep found through EXOSAT observations of PSR 1929+10.[9]

3. Neutron Star Precession and the Neutron Matter Equation of State

Trumper et al.,[10] on the basis of their EXOSAT observations of Her X-1, have concluded that the clock mechanism for its 35-day cycle is the free precession of the neutron star. Since the existence of a stable free precession mode requires a solid crust astronomical object, it is intuitively obvious that the wobble frequency will depend upon the extent of the neutron star crust. Calculations based on various models for the equation of state of neutron matter show that the crustal extent is determined primarily by the stiffness of the equation of state for neutron matter at densities $\rho \gtrsim \rho_o$. If one makes the "Occam's razor" assumption that all neutron stars possess nearly the same mass ($\sim 1.4 M_\odot$) and that the initial spin period, P_o, of Her X-1 is not far from that inferred for the Crab pulsar ($P_o \sim 15$ms), the identification of the 35^d period as stellar wobble leads to the conclusion[1] that the equation state of neutron matter is comparatively stiff, somewhat stiffer indeed than one would conclude from the microscopic calculations of Friedman and Pandharipande.[11]

Alpar and Ögelman have shown how vortex creep enables the rotation vector of the pinned superfluid to follow the precession of the crust.[12] As Alpar discusses elsewhere in these Proceedings,[3] further accretion torques on the crust of the star are likely large enough to balance the internal torques applied by the creeping crustal superfluid. A further requirement is that these need to act in phase with the wobble in order to pump it to the magnitude required by observation; thus one needs to posit a wobble-operated accretion gate.[13]

4. Conclusion

In the Table, taken from Ref. 1, the predictions of neutron matter theory for various density regions in the star are summarized, as are the observational consequences of those predictions. Pulsar timing irregularities provide the principle probe of the superfluid neutron stellar interior. In view of the excellent agreement between vortex creep theory and the observed behavior of the Vela and Crab pulsars, and of PSR 0525-21, following giant glitches, it could be argued that timing irregularities provide us with more detailed information about the interior of a neutron star than, to date, observations of "regular" pulsar behavior provide us with a detailed picture of the particles and fields outside the star responsible for characteristic pulsar radiation.

There remain a number of challenging problems concerning the structure and physical behavior of neutron stars. For example, while vortex creep theory has been extremely successful in describing the postglitch behavior of the Vela pulsar, following its giant glitches, as well as the Crab pulsar and PSR 0525+21 following their large glitches, the postglitch relaxation observed following the recent glitch from PSR 0355+54 is different from that observed for the other pulsars.[14] This is perhaps not surprising, since the relative magnitude of the glitch, $|\Delta P/P| = 4.4\times10^{-6}$, is the largest observed to date, as is the relative magnitude of the jump in the period derivative $|\Delta\dot{P}/\dot{P}| = 0.10 \pm 0.04$. It is quite possible that under these circumstances, in which $10 \pm 4\%$ of the moment of inertia of the neutron star is involved in the glitch, different, and possibly new regimes of vortex creep will play a role.

Such a large inertial moment for the pinned neutron superfluid is easily accomodated in neutron star structures calculated from an equation of state sufficiently stiff to yield the 35^d wobble period of Her X-1. However, such pinned superfluid inertial moments would not exist for stellar models of $1.4M_\odot$ neutron stars with an equation of state which is appreciably softer. Given the fact that constraints on the mass-radius relation for neutron stars,[15,16] which are obtained by combining theory with observation for X-ray bursts assuming this mass value, favor softer equations of state, it would seem that if both the identification of the 35^d periodicity in Her X-1 and the current canonical description of X-ray bursts are to be correct, then the neutron stars being observed in these two cases must have rather different masses.

Another challenging problem is the calculation of the pairing energy gaps for neutron matter at densities between 10^{12}gm cm^{-3} and nuclear matter density. Current theoretical calculations yield widely disparate values; it appears likely that the constraints placed on these energy gaps by post-glitch behavior and vortex creep heating of old neutron stars will be decisive in sorting out the correct theoretical description. Indeed, it is increasingly clear that neutron stars provide the only observational constraints on the description of neutron matter.

Finally, there is the issue of the nature of neutron star matter at densities greater than nuclear matter density, ρ_o. While strange matter, because it leads to strange stars with no internal structural differentiation, can be ruled out by the observation of glitches,[17] the appearance of a pion condensate in this region continues to be a distinct possibility; and might be required to explain the cooling curves of young neutron stars.[4]

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Table - Neutron Stars as Cosmic Hadron Matter Laboratories

Density range of Hadron Matter	Theoretical Predictions	Observational Consequences
$\frac{\rho_o}{500} \lesssim \rho \lesssim \rho_o$	o Superfluid crustal neutrons o Pinning of superfluid vortices to crustal nuclei o Vortex creep theory of postglitch relaxation o Internal temperature of glitching pulsars o Vortex creep heating of old neutron stars o Wobble period fluctuations	o Origin of macroglitches in the Vela and other pulsars o Postglitch behavior and surface temperatures of Vela and PSR 0525+21 o Surface temperatures of old neutron stars o Changes in wobble period
$\rho \gtrsim \rho_o$	o Equation of state of neutron matter can be soft or stiff o Crustal extent, wobble period, M-R relation, M_{max}, and starquake frequency are sensitive e.o.s. barometers	o 35^d periodicity observed in Her X-1 o Initial spins of Her X-1 like stars o Starquakes in Crab and other very young pulsars
$\rho \gtrsim 2\rho_o$	o Possible exotic new forms of matter, such as pion condensates, quark liquids, which lead to novel cooling mechanisms	o Reduced surface temperatures of young neutron stars

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